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Supersymmetric Model for Neutrino Magnetic Transition Moment

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Abstract

A supersymmetric model for a large neutrino magnetic moment is presented. The neutrino mass is protected by an approximate horizontal symmetry. The model possesses an unbroken $l_e - l_\mu$ symmetry which enforces the equality of the electron and muon neutrino masses. We find that for a 10 eV neutrino, the neutrino can have a magnetic transition moment up to $10^{-12}\mu_B$ without tuning of parameters. With tuning, the mass can be further suppressed or the magnetic moment correspondingly increased.

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1. Introduction

Recent data from the Cl-Ar neutrino detector continues to suggest an anti-correlation of solar neutrino flux with the sunspot cycle [1]. It has been suggested that such a correlation might be explained by a large magnetic moment for the neutrino [2]. The magnetic field in the sun could then transform the neutrinos to a species which does not react with the detector.

There are two different types of magnetic moment which could be of interest. A Dirac-type magnetic moment would transform the neutrino to a sterile right-handed neutrino. Supernova data put stringent constraints on Dirac magnetic moments, so such models are disfavored [3]. The other type of magnetic moment is a Majorana transition moment between left-handed neutrinos of different species. We will concentrate on the Majorana magnetic transition moment between $\nu_e \nu_\mu$.

To explain the solar neutrino data, a large magnetic moment on the order of $10^{-11}\mu_B$ is required. However, such a large magnetic moment would seem to be inconsistent with experimental limits on the mass of the neutrino. If a neutrino magnetic moment is generated by a diagram with heavy particles of mass M, then the same diagram with the photon line removed will give a contribution to the neutrino mass. One would then expect that $\mu_\nu / m_\nu \approx e/M^2$. For masses of order M_W this ratio is $\approx 10^{-4}\ e/\mathrm{GeV}^2$, which would put a limit of $10^{-15}\mu_B$ on the magnetic moment.

Various mechanisms have been suggested to provide an additional suppression of the neutrino mass, lifting this constraint [4]–[10]. One observation, due to Voloshin [11], is that if we identify an SU(2) symmetry which acts on the space of $(\nu\, \nu^c)$ then the Majorana mass term is a triplet while the magnetic moment is a singlet. The mass would then be forbidden, but μ_ν is unconstrained. Such a symmetry would most likely be broken in nature, which would lead to a non-zero mass, but under favorable circumstances it may provide sufficient suppression.

2. Supersymmetric Model of Neutrino Magnetic Moment

To construct a model in which the neutrino gets a large magnetic moment without violating experimental limits on the neutrino mass, we start with the minimal supersymmetric extension of the standard model. This model possesses an approximate horizontal symmetry between the e–μ families. This symmetry is broken, as evidenced by the mass difference between the electron and muon, but as we shall see, it may be able to do what we want. We therefore impose the condition that this horizontal symmetry be respected in our theory, except by the Yukawa couplings which generate the fermion masses (and possibly the corresponding soft SUSY-breaking parameters). Also we impose an unbroken global $l_e - l_\mu$ symmetry. This guarantees that the electron and muon neutrino will remain degenerate in mass, so the magnetic transition in the sun will be efficient.

In addition to these symmetry constraints, we require a lepton number violating interaction which will generate the transition magnetic moment $\frac{1}{2}\nu_e{}^T c^{-1}\sigma_{\alpha\beta}\nu_\mu F^{\alpha\beta}$. To do so we introduce an additional superfield Ψ which is an $SU(2)_L$ singlet, with hypercharge $Y = 2$. We also introduce a new doublet field H_ψ with $Y = -1$. This field is required to mix the fermionic partner of Ψ with the wino after SU(2)-breaking. Further additional fields must be introduced to cancel anomalies, but these fields need not play any role here.

These new fields have the structure to be interpreted as an additional generation of leptons. In fact, in a model constructed along these lines [9], Babu and Mohapatra identified these fields with those of the tau lepton. This has the advantage of economy but has some difficulty in generating the large neutrino magnetic moments desired. We will not attempt to identify these fields in such a way. Rather, we will introduce them in a general and natural way, consistent with the symmetry constraints described above.

The relevant fields are L_e, L_μ, H_d, H_ψ, transforming under $SU(2)_L \times U(1)_Y$ as (2,-1); e^c, μ^c, Ψ transforming as (1,2); and H_u transforming as (2,1). H_u and H_d are the Higgs superfields of the minimal model, which get vevs v_u, v_d to provide fermion masses. The part of the superpotential depending on these fields is:

$$\begin{aligned} W = h_e L_e H_d e^c + h'_e L_e H_\psi e^c + h_\mu L_\mu H_d \mu^c + h'_\mu L_\mu H_\psi \mu^c + f' H_\psi H_d \Psi \\ + m_H H_u H_d + m'_H H_u H_\psi + f L_e L_\mu \Psi \end{aligned} \tag{2.1}$$

It is important to remember that this is not the full superpotential. In particular we have suppressed the parts of the superpotential which result in non-zero vevs for the Higgs fields. Also note that since H_ψ and H_d have the same quantum numbers, they will in general mix. We choose a basis such that only H_d gets a vev. Due to this mixing, however, it is to be expected that h, h' as well as m_H, m'_H will be of the same order of magnitude. The Yukawa couplings h_e and h_μ are responsible for the lepton masses; their difference $h_\mu - h_e$ represents the effect of horizontal symmetry breaking.

Each term in the superpotential may have a corresponding term in the soft supersymmetry breaking Lagrangian. The SUSY-breaking Lagrangian also contains mass terms for the scalar superpartners and gauginos. We make the requirement that these terms all respect the horizontal symmetry at least to the same order as the supersymmetric part of the theory. Thus the mass difference between the scalar leptons will be at most of the order of the mass difference between the leptons.

The fermionic partners of the new fields Ψ and H_ψ (denoted here by ψ and h_ψ respectively) mix in the chargino and neutralino sectors. In particular, the chargino mass matrix is (in two component notation):

$$\text{mass term} = \chi^+ M \chi^- \tag{2.2}$$

where $\chi^+ = (\tilde{w}^+, h_u^+, \psi)$, $\chi^- = (\tilde{w}^-, h_d^-, h_\psi^-)$ and the mass matrix M is given by:

$$M = \begin{pmatrix} M_{\tilde{w}} & \sqrt{2} M_W \sin\beta & 0 \\ \sqrt{2} M_W \cos\beta & m_H & 0 \\ 0 & m'_H & m_\psi \end{pmatrix} \tag{2.3}$$

Here the angle β is defined by $\tan\beta = v_u/v_d$ and $m_\psi = f' v_d$. This matrix is restricted only by the requirement that the lightest eigenstate be sufficiently heavy to be consistent with experimental (non-)observation. The neutralino sector is similarly restricted, with constraints arising from the width of the Z boson.

The diagram which generates off-diagonal neutrino mass is shown in fig. 1. One vertex arises from the lepton number violating interaction proportional to f; the other is a standard supersymmetric weak interaction vertex. There are two such diagrams related by the interchange ($\nu_e \leftrightarrow \nu_\mu$, $\tilde{e} \leftrightarrow \tilde{\mu}$). The f vertex is antisymmetric under this interchange, so the diagrams would cancel in the limit of exact horizontal symmetry. The magnetic moment does not cancel because the direction of charge flow in the loop also changes under the interchange, giving another sign change when we couple a photon to the charged particles in the loop.

Other authors [9][10] have considered a similar model, concentrating on the diagram shown in fig. 2. Here one vertex is proportional to f; the other is proportional to h'_e or h'_μ. The diagram also is proportional to the mixing angle in the ($\tilde{e}_L\, \tilde{e}_R$) or ($\tilde{\mu}_L\, \tilde{\mu}_R$) sector, and of course it depends on the mass of the scalar lepton. There are several additional opportunities for the horizontal symmetry breaking to spoil the cancellation in this diagram; in particular, there is no reason why $(h'_\mu - h'_e)/h'_\mu$ should be small since $(h_\mu - h_e)/h_\mu$ is not. (Even if this were so in one basis, we would expect that the H_ψ-H_d mixing would spoil it in the basis we are using.) Let us rather assume that the mixing in the scalar lepton sector is small enough that we may neglect this diagram, and concentrate on fig. 1.

3. Computation of Mass and Magnetic Moment

In the diagram of fig. 1, the neutrinos couple to the scalar lepton and to a general chargino state. In order to calculate the diagram, we must express the chargino states to which the neutrinos couple in terms of the mass eigenstates. This may be done by diagonalizing the mass matrix in eq. (2.3). Although the matrix may in principle be diagonalized analytically, it is more convenient to express the procedure in the following form. The neutrinos couple to the fields ψ (through the lepton number violating interaction), and $\tilde{w}^-$ (through the weak interaction). Write these states in terms of the mass eigenstates $\chi_i^{\pm}$:

$$\begin{aligned} \psi &= U_j \chi_j^+ \\ \tilde{w}^- &= V_j \chi_j^- \end{aligned} \tag{3.1}$$

The couplings U_j and V_j can be evaluated numerically when the parameters in the mass matrix are given values.

Using this notation, the results of the calculation may be written down compactly:

$$\begin{aligned} m_\nu &= fg \sum_j U_j V_j M_j \big(I_1(M_{\tilde{\mu}}, M_j) - I_1(M_{\tilde{e}}, M_j) \big) \\ \mu_\nu &= efg \sum_j U_j V_j M_j \big(I_2(M_{\tilde{\mu}}, M_j) + I_2(M_{\tilde{e}}, M_j) \big) \end{aligned} \tag{3.2}$$

The dependence of this result on the parameters of the theory enters through the chargino mass eigenvalues M_j. The functions I_1 and I_2 represent the results of the momentum integrals and may be written exactly. The mass integral is logarithmically divergent, but the difference is finite, and so is the neutrino mass. Only the relevant part (which contains the dependence on $M_{\tilde{e}}$) is presented here.

$$\begin{aligned} I_1(M_{\tilde{e}}, M_j) &= \frac{1}{16\pi^2} \frac{\ln x_j}{1 - x_j} \\ I_2(M_{\tilde{e}}, M_j) &= -\frac{1}{16\pi^2 M_{\tilde{e}}^2} \left[\frac{\ln x_j}{(1 - x_j)^2} + \frac{1}{1 - x_j} \right] \end{aligned} \tag{3.3}$$

where $x_j \equiv M_j^2 / M_{\tilde{e}}^2$.

According to our prescription, the approximate horizontal symmetry tells us that the scalar electron and scalar muon are nearly degenerate. We write $M_{\tilde{\mu}}^2 = M_{\tilde{e}}^2(1 + \Delta)$ and expand eq. (3.2) to the lowest order in Δ. The resulting expressions for the mass and magnetic moment are:

$$\begin{aligned} m_\nu &= \frac{fg}{16\pi^2}\Delta \sum_j \left\{ -U_j V_j M_j \left[\frac{x_j \ln x_j}{(1-x_j)^2} + \frac{1}{1-x_j} \right] \right\} \\ \mu_\nu &= \frac{fg}{8\pi^2}\frac{e}{M_{\tilde{e}}^2} \sum_j \left\{ -U_j V_j M_j \left[\frac{\ln x_j}{(1-x_j)^2} + \frac{1}{1-x_j} \right] \right\} \end{aligned} \tag{3.4}$$

The expressions in the braces are similar but not equal. Generically, they will be of the same order of magnitude, and we see that as expected, the ratio μ_ν/m_ν has been enhanced by a factor $1/\Delta$.

We now must consider what are natural values for Δ. Of course the supersymmetric contributions to the scalar lepton mass-squared matrix will make a contribution to Δ of order $m_\mu^2/M_{\tilde{e}}^2$ which is of order 10^{-6} or smaller. This is the smallest reasonable value. There may also be contributions to Δ from the supersymmetry breaking sector. The magnitude of these contributions depends on the specific mechanism of horizontal symmetry breaking. In the simplest model, horizontal symmetry is broken explicitly by Yukawa couplings. Then the SUSY-breaking Lagrangian contains terms:

$$\mathcal{L}_{SSB} = A_e h_e \tilde{L}_e H_d \tilde{e}^c + A_\mu h_\mu \tilde{L}_\mu H_d \tilde{\mu}^c + \cdots \tag{3.5}$$

where A_e, A_μ are arbitrary soft supersymmetry breaking parameters with dimensions of mass. In many theories, these parameters are expected to be equal and of the same order as $M_{\tilde{e}}$. Then these terms would imply that $\Delta \approx m_\mu/M_{\tilde{e}} \approx 10^{-3}$. In this case, for a 10 eV neutrino, the magnetic moment is around $10^{-12}\mu_B$. It is possible, however, that in some models of e–μ mass splitting, the SUSY-breaking Lagrangian will respect the horizontal symmetry more than the effective Yukawa couplings h_e, h_μ. It is also possible to tune the parameters of the model so that one or the other of the quantities in braces in (3.4) is small or even zero. Thus we may achieve a higher ratio of μ_ν/m_ν if we allow some tuning.

As an example, let us consider some values. Take $\tan\beta = 2$, $m_H = m'_H = 200$ GeV, $M_{\tilde{e}} = 100$ GeV, $m_{\tilde{\psi}} = 150$ GeV, $\tan\beta = 2$, and $M_{\tilde{w}} = 300$ GeV. Then for $fg = 10{-}3$ and $\Delta = m_\mu/M_{\tilde{e}}$ we get $m_\nu = 3$ eV and $\mu_\nu = 0.5 \times 10^{-11}\mu_B$. The lightest chargino state in this case is 90 GeV. This represents a tuning of parameters to suppress the mass by order 10^{-1}. Lowering m_H to 150 GeV lowers the neutrino mass to 0.5 eV without significantly affecting the moment, corresponding to an even greater tuning. There is a wide range of realistic parameters for which the mass is suppressed by an order of magnitude compared to the moment.

4. Phenomenological Implications

The phenomenological implications of this model are similar to those considered in ref. [9]. Rare decays such as $\mu \to 3e$, $\mu \to e\gamma$ are forbidden by the unbroken $l_e - l_\mu$ symmetry. There is an additional contribution to μ decay proportional to f^2/M_Ψ^2. To be consistent with universality, this must be less than a couple percent of G_F, which for $M_\Psi = 300$ GeV requires that f be smaller than 10^{-1}.

To ensure the consistency of our model, we should calculate the numerical factors for representative values of the parameters of the theory. We must then determine the strength of the coupling f which is required to saturate the limits on neutrino mass and moment, and check to see that this does not introduce contradictions with observed low energy physics.

For scalar lepton masses of 100 GeV, and other masses in the range 100-500 GeV, the quantities in braces in eq. (3.4) are around $10^{-2}M_{\tilde{s}}$. (It should be noted that this value is small because there is no direct mixing of ψ with $\tilde{w}^-$, so that fig. 1 is proportional to a product of mixing angles rather than a single mixing angle.) To achieve the largest possible magnetic moment we choose the coupling f such that $m_\nu = 10$ eV. This gives $fg \approx 2 \times 10^{-3}$. This is easily consistent with the limit given by μ decay.

It is also interesting to consider the case where the Ψ, H_ψ superfields are identified with the tau lepton [9][10]. In this case, we must identify $m_\psi = m_\tau$, and we must ensure that the τ neutrino is light enough to satisfy experimental bounds. This requires $m'_H < 10$ MeV for the cosmological bound $m_{\nu_\tau} \leq 100$ eV. This model has several interesting phenomenological consequences, but for our current concerns, the relevant point is that fig. 1 is suppressed. This is due to the fact that m_τ and m'_H are responsible for the mixing of the right-handed τ with the wino in fig. 1. The overall suppression is of order 10^{-4} which cannot be compensated by raising the coupling f without violating the constraints due to μ decay. In this case, it is probable that fig. 2 will dominate the neutrino magnetic moment (see ref. [10] for a discussion of the limits on μ_ν in this type of model).

In conclusion, we have constructed a softly broken supersymmetric model with a lepton number violating interaction and approximate horizontal symmetry which naturally leads to a transition magnetic moment for the neutrino of $10^{-12}\mu_B$ for a neutrino mass of 10 eV. If the parameters of the theory are tuned or the horizontal symmetry is less severely broken in the SUSY-breaking sector, the magnetic moment can be increased to 10^{-11} or even higher.

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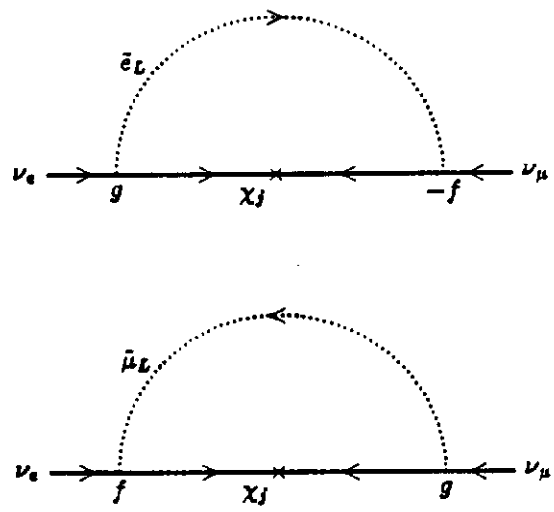
Figure Captions

Fig. 1: Dominant diagrams contributing neutrino mass. The arrows on the scalar lines indicate the direction of positive charge flow.

Fig. 2: Sub-leading diagrams for the neutrino mass.



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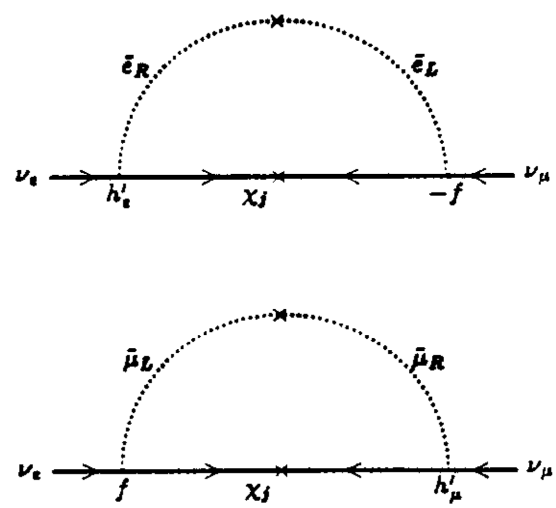

Figure 2: Subleading diagrams for the neutrino mass.